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HYBRID PROPULSION SYSTEMS FOR MOTOR VEHICLES WITH
PREDOMINANTLY INTERMITTENT MODES OF OPERATION

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HYBRID PROPULSION SYSTEMS FOR MOTOR VEHICLES WITH PREDOMINANTLY INTERMITTENT MODES OF OPERATION*

/141[#]

H. Bartsch, J. Helling, H. Schreck

A small delivery vehicle was equipped with a flywheel-hybrid drive and compared in test-stand and driving tests with a conventional-drive vehicle. It turned out that with the hybrid drive, energy can be saved and exhaust emissions can be reduced.

1. Posing the Problem

The drive stress on vehicles employed in large cities is characterized by high dynamics. Because of the severe drop in efficiency - particularly of internal combustion engines - in the low load range and the required transformation of the characteristic, this mode of operation is not very effective. Since for intermittent operation, significant amounts of kinetic vehicle energy must be available, the energy consumption of a vehicle in this operating mode increases over a vehicle in constant operation.

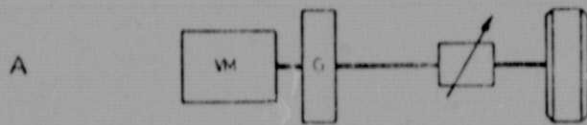
The internal combustion engine cannot be replaced at the moment because of its many other advantages; however, a reduction of its energy consumption under the given operating conditions by a hybrid drive is possible. The use of an energy buffer as an accessory will reduce these employment- and system-induced disadvantages.

Of the primary energy storage batteries [1] under consideration, only accumulator batteries and flywheels can be discussed because of energy and performance reasons. The requirement for a short-term, high power output with acceptable energy storage capacity is met more closely by the flywheel. Moreover, it avoids losses of energy conversion which should also be avoided in the power control element, if possible.

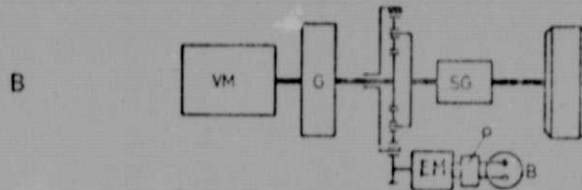
*The paper is a summarization of a lecture presented to the 4th status seminar on "Vehicle and Traffic Technology" of the BMFT and the 2nd annual meeting of the VDI Society of Vehicle Technology, 10-12 Nov., 1976, Congress Hall, Berlin.

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Basic Structure with continuous transmission.



Basic structure with planetary gear train and control unit.



Basic structure with planetary gear train and secondary gear train.

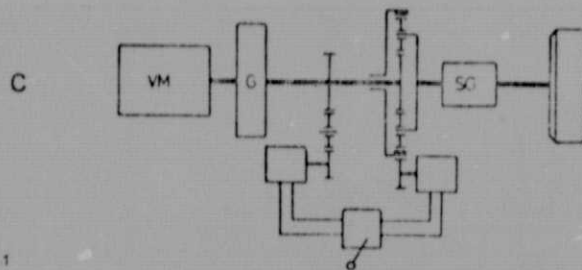


Figure 1: Structure variations of the hybrid drive with flywheel.

Symbols, Indices, and Abbreviations

A	Air resistance surface area	P_{LVL}	ventilator power loss
a	acceleration	R_S	flywheel radius
B	battery	S	flywheel
c_W	air resistance coefficient	SG	shifting transmission
EM	electric motor	t	time
f_D	dynamic factor	VM	internal combustion engine
G	transmission	v	vehicle speed
M	torque	W	energy
m	vehicle mass	W_{kin}	vehicle kinetic energy
m_s	flywheel mass	x	path
n	RPM	η	efficiency
P	power	ω	angular velocity

Because of the lack of purely mechanical regulating units for high power outputs, a planetary gear train with additional control units was used; Figure 1 (design A). Since the use of an electric control unit with accumulator battery also presents the possibility of brief,

emission-free operation, this mode of operation was selected (design B). The operating behavior of this type of control unit is generally equal to that of a pure controlled transmission with two electric units (design C) so that the test results could also be applied to this mode of operation which is somewhat simpler, cheaper, and more economical.

The problem consisted in demonstrating functionality in practical tests and to illustrate how much the theoretically-significant energy savings is reduced by system-induced losses - in addition to continuing theoretical investigations to produce the suggested drive system.

2. Theoretical Investigations

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The theoretical energy storage values of over 60 Wh/kg with metal flywheels can only be attained with large diameters with attendant (air) evacuation: "super flywheels" with significantly greater energy densities [2-4]. Such flywheels are being studied but are not available at present. Operating values for steel flywheels are available [5] where material utilization values up to about 30% were realized. If the evacuation is to be omitted, the ventilator power loss must be minimized. Design and ventilator power loss guidelines are shown in Figure 2 for a certain energy storage value. The flywheel mass results from the possible RPM n_s and the permissible power loss P_{LVL} .

The important component of the transmission with infinite control ratio used for power control of the flywheel is the planetary gear train. Since the control mechanism power should be kept small for reasons of weight and cost, the ratio of the control unit power to the power given off or absorbed should also be minimized. From considerations of power and RPM [6, 7] there resulted a limited control region of the transmission, Figure 3.

The RPM reduction when the flywheel gives off energy reduces the favorable control region of the planetary gear train also. The requirement for a large RPM-range can be met by the additional employment of a gear transmission.

The electric unit as an active control element combines the advantages of good controllability, high reliability and low noise; in addition it makes possible the advantageous four-quadrant operation and is available in a relatively high-performance design as a result of intensive work on the electric automobile.

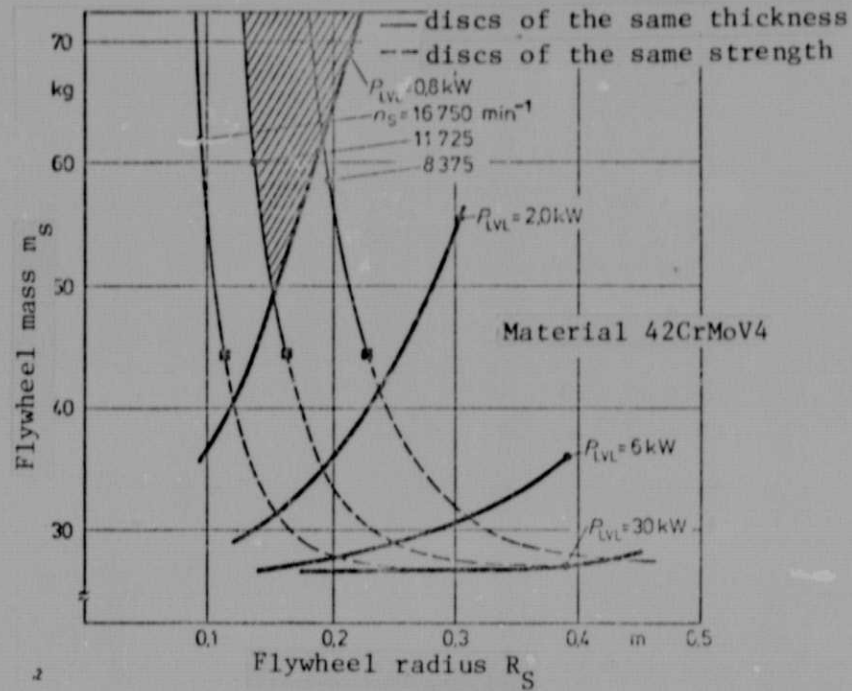


Figure 2: Diagram of the flywheel design ($W_{Smax} = 128 \text{ Wh}$).

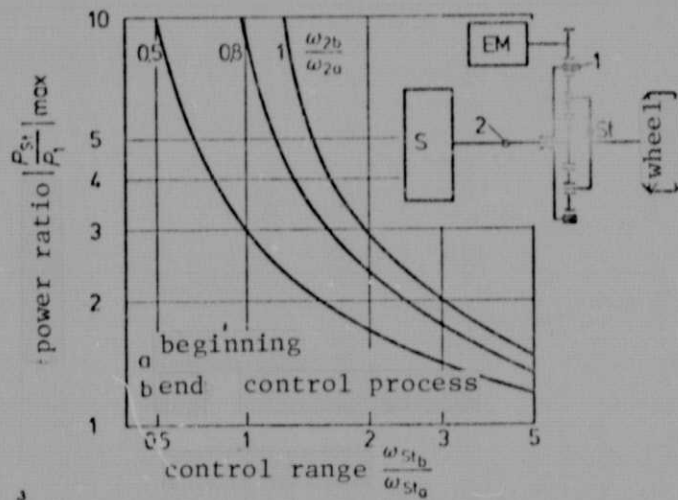


Figure 3: Power ratios and control regions of planetary gear trains.

3. Preparation of the Drive System and Test Vehicle

A drive design for axis-parallel arrangement has been worked out with the components internal combustion engine, flywheel, planetary gear train and electric control unit, Figure 4. For reasons of manufacture the flywheel shaft was designed vertically on floating bearings.

The diagonal assembly of the drive caused by the available room and the necessary adaptation to the two- and four-gear transmission required an additional angular drive between the drive and gear transmission.

Except for casting and gearing work, the planetary transmission block including flywheel has been completed. The 11-kW electric unit with two-quadrant control comes from Bosch Co.; a Fichtel & Sachs Wankel engine was the first internal combustion engine used; later, a Fiat 126 engine was employed.

The electronic system was prepared after great efforts. Beginning from the Bosch control, additional functions like four-quadrant operation with two-pedal logic, an automatic starting control, RPM controls, throttle control of the engine with appropriate components were designed. The drive unit was built into a small delivery vehicle, Figure 5. Its engine space had to be changed only a little. All control parts were located under the rear seat, the battery consisted of 12 units, each with 45 Ah, located under the middle seat-bench, Figure 6. This test vehicle can be compared to a conventional vehicle of comparable design. Since a smaller, lighter engine is used with the hybrid drive, but flywheel electric unit, planetary gear train and battery must be added, the hybrid vehicle has a clearly greater mass. In this comparison, keep in mind that the hybrid vehicle was designed only in a single test design whose inherent weight could not be minimized like that of the mass-produced vehicle.

For otherwise similar vehicle conditions, the mass for the hybrid vehicle was 1,722 kg (of this, 200 kg for the battery), and for the mass-produced vehicle with 1.7 liter engine, 1340 kg.

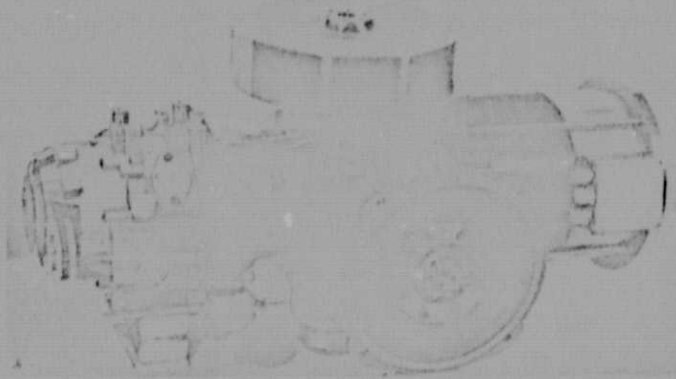


Figure 4: Hybrid Drive with Flywheel.



Figure 5: Drive in the Test Vehicle

4. Comparison of the Hybrid-Powered and Conventional Vehicles

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The hybrid vehicle was driven on the Institute's rolling test stand and on a test strip. Figure 7 shows its acceleration curves as they compare to the curves of mass-produced vehicles from the literature [8, 9].



Figure 6: Test Vehicle with Hybrid Drive

For the hybrid vehicle the somewhat slower start-up from a stopped position is striking. After initial acceleration, it increases speed at about a constant tractive power. In the velocity range under consideration we can call the driving dynamics about equal - even during braking.

In order to get a general overview of the behavior of the vehicles in cyclic operation, we did not compare single, known cycles, but cycles of different dynamics and speed. Examples for this are shown in Figure 8. Overall, maximum cycle speed from 30-50 km/h and dynamic factors [10] from about $10-50 \times 10^{-3}$ were used.

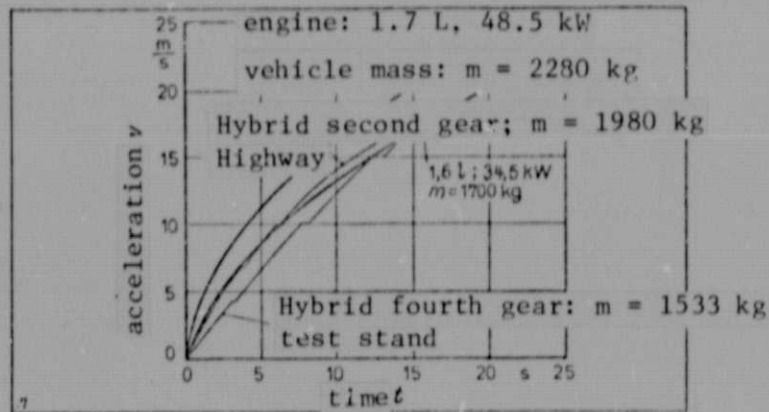


Figure 7: Acceleration Comparison of Hybrid and Conventional Test Vehicles.

4.1 Component Results

We next examined the conditions for favorable operation of the internal combustion engine and tried to determine the operating range of the internal combustion engine for predominantly dynamic operation of the vehicle. For a range of dynamic factors from 10^{-3} to 35×10^{-3} , maximum cycle speeds from 30-50 km/h and stopping periods up to 60%, the operating range is in the overlapped characteristic performance graph of the Wankel engine and the Fiat engine, shown in Figure 9. With this result the drive completely meets the operating conditions for the internal combustion engine. /144

The flywheel as a short-term energy storage device should be operating only during intermittent operation. Its power output and absorption should be considered primarily in connection with the vehicle's kinetic energy. Figure 10 shows data with regard to this which was determined from measured recordings. Due to the constant sign of energy losses, the energy conversion of the flywheel during acceleration must be greater than during braking. As a result of the additional intermediate storage of control-unit-battery energy, there results somewhat greater values than are appropriate to the vehicle's kinetic energy. The reduction in the requirement of mechanical energy due to the storage and reuse of kinetic braking energy can be determined by the energy recycling efficiency η_{rec} defined for the driveshaft.

An exact determination of this quantity is difficult, however, since the efficiency with which this stored energy is given off to the wheel can hardly be determined separately. If we set this value at 0.8, then from the measured recordings the values for η_{rec} shown in Figure 11 are

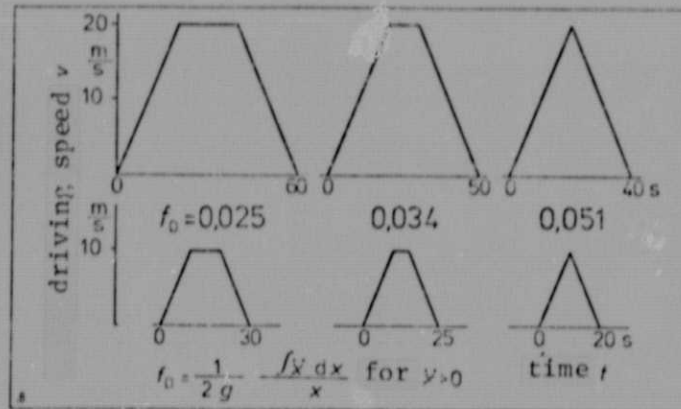


Figure 8: Comparison of different driving trips and dynamic factors.

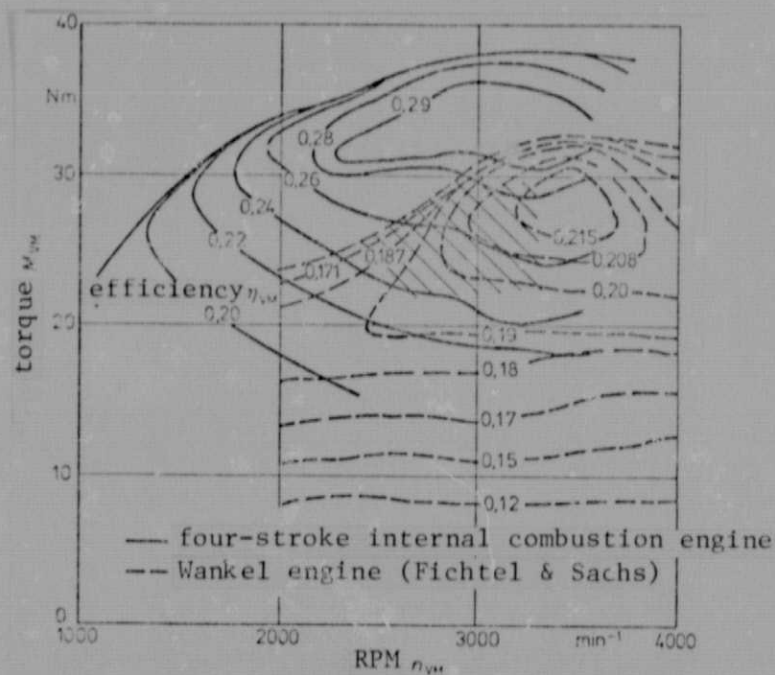


Figure 9: Consumption characteristics for 4-stroke internal combustion and KM 20W Wankel engine.

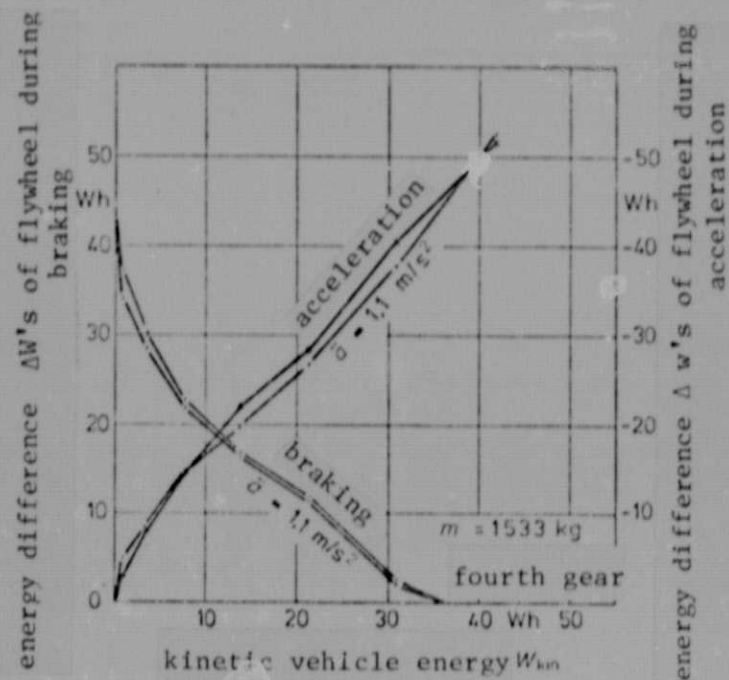


Figure 10: Kinetic energy of flywheel and vehicle during acceleration and braking.

determined. The average values of the entered points fall together with the initial velocity since here the losses in the control unit are of greater importance. Overall, the level is clearly higher than is seen in purely electric drives, for example.

With the use of one of the electric control unit's batteries, either the range is limited or its energy conversion must exhibit an equalized balance. But since at present no suitable measurement instrument exists for detection of the momentary battery charge-status, this balance cannot be verified. Thus the corresponding losses cannot be included in the evaluation. By means of a watt-hour counter, however, the energy conversion to the battery terminal was determined so that the operating conditions for use of a storage battery was shown at the control unit. It turned out after individual cycles that energy losses always occurred in the electrical system. In this case, they were determined by the stopped times needed for recharging the battery. This effect worsened the energy balance during unusually long stopped times because of the high flywheel RPM and planetary gear train. It did not occur in the regenerating system with double convertor.

4.2 Comparison of Energy Conversion

With the conditions of an equalized energy balance at the battery

terminal, comparisons of energy consumption for the conventional and hybrid vehicles could be determined from the cyclic driving, Figure 12. Here, we do not use the results obtained for the hybrid vehicle with Wankel engine, but those from the 4-stroke internal combustion engine. Both vehicles were driven on a rolling test stand with the same simulated loads of 1533 kg and dynamic factors from about $10-35 \times 10^{-3}$ at maximum cycle speeds of 14 m/s. The study proved in particular - at

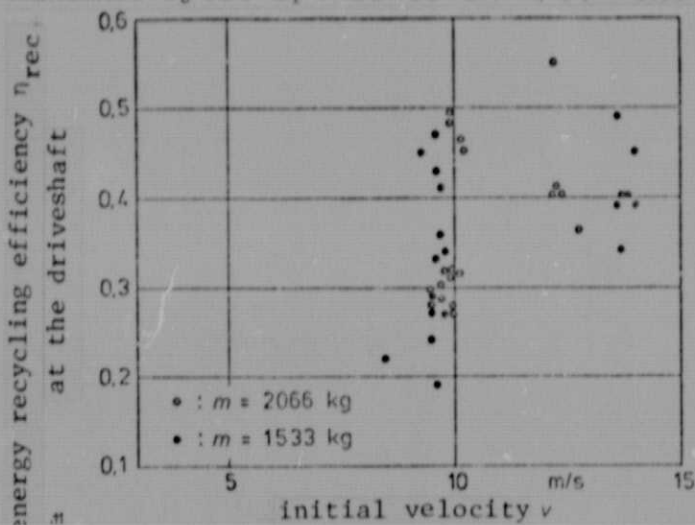


Figure 11: Energy recycling efficiency related to the driveshaft of the test vehicle.

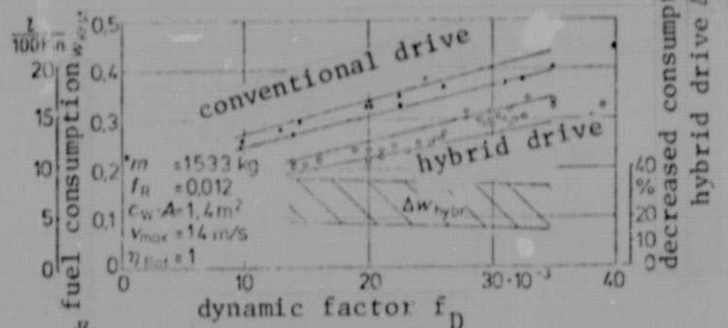


Figure 12: Comparison of energy consumption of vehicles of the same mass.

low dynamics for this case-decreased consumption of 15-35%. If cycles of only up to 10 m/s are driven, the results are slightly better [11].

From the energy conversion at the battery, one can estimate its losses related to the entire energy conversion. If the energy consumption is related to the same payload, there results the illustration in Figure 13. Here, in the first quadrant we see the mechanical energy requirement of the vehicle with and without regenerative braking plotted against the dynamic factor. Between fuel energy and drive energy, in the second quadrant there is an average efficiency of 8-10% for the conventional vehicle. If we include the battery losses, this value is lower still for the hybrid drive. The losses of this first test vehicle significantly reduce the engine operating at about 26% efficiency and the favorable mechanical energy requirement. If we include the payload factor, a decreased consumption of about 10% results in this case.

An energy balance for the regenerating system can be established

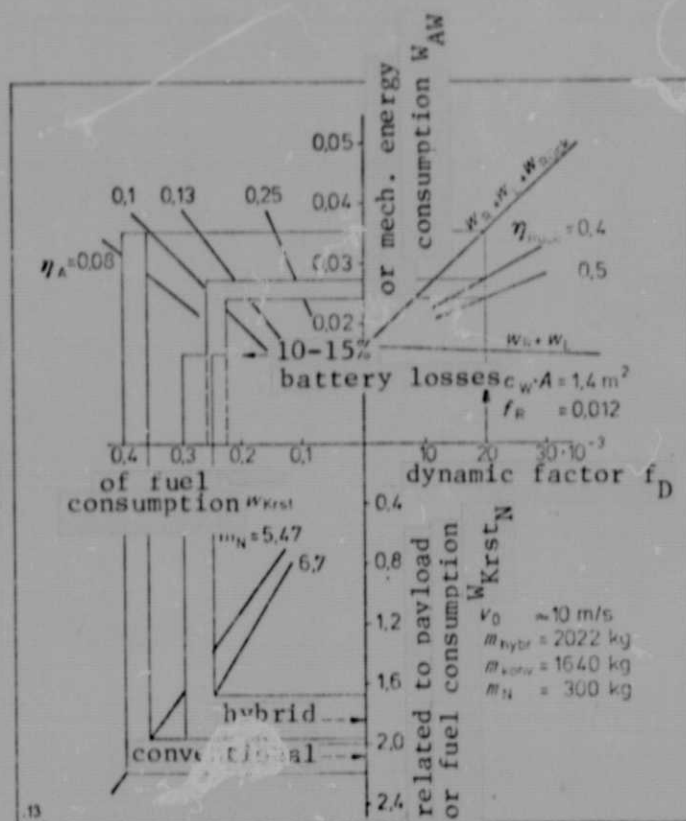


Figure 13: Comparison of energy consumption of the test vehicles with the same payload, with control battery of the hybrid vehicle.

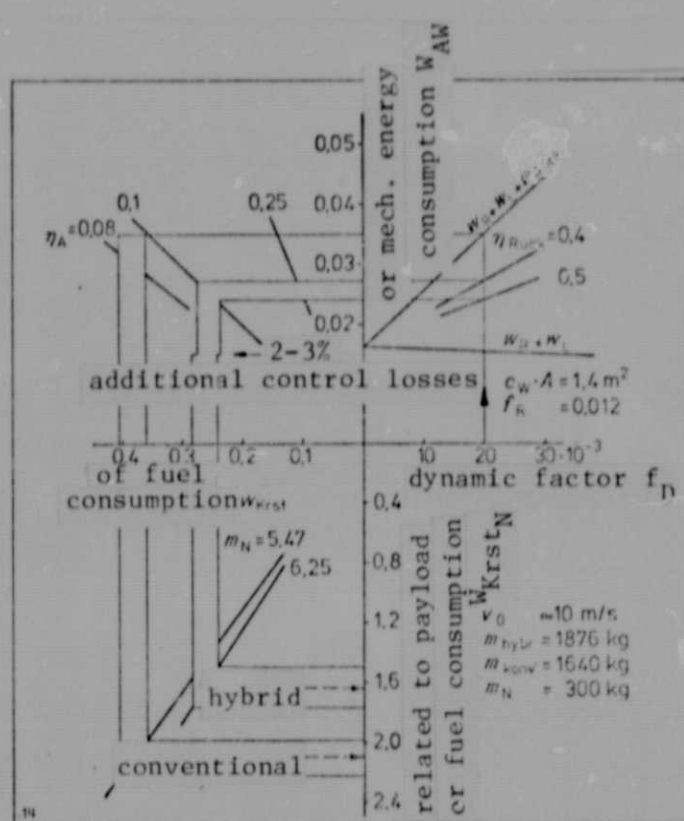


Figure 14: Comparison of energy consumption of the test vehicles of the same payload with regenerative drive system of the hybrid vehicle.

with the available test results if we use a second electric unit (Figure 14) instead of the battery. In this case, however, significantly lower additional losses occur (compared to the available test values) so that the unfavorable effects of long stopped times on the hybrid drive are not considered.

In the third quadrant of the figure, the better drive mass is considered. The balance exhibited an average decreased consumption of about 25% in spite of additional, unfavorable operating conditions which will not be discussed here.

5. Summary

A drive design was prepared with the purpose of improving the use of the internal combustion engine during predominantly intermittent operation of vehicles and high-efficiency energy storage. This drive design can be operated emission-free for brief periods of time at

reduced power. This system - characterized primarily by the combination of an internal combustion engine with a flywheel short-term energy storage unit which effects the power control of the flywheel by an electrically-controlled planetary geared transmission - was prepared and examined in practical tests. In this, the suitability of the flywheel was demonstrated for disconnecting the internal combustion engine from direct power output and high-efficiency regenerative braking was demonstrated in practical tests. It was also determined that the power control with the planetary gear train is advantageous if its favorable operating range is expanded by a gear transmission to a large control range. The control of this transmission by an electrical unit with battery is only meaningful if short-term emission-free operation is of great importance. The use of a planetary gear train controlled by a double convertor proved better in energy consumption. This makes possible lower masses and smaller losses together with reduced control requirements. /146

The tests sometimes performed in unfavorable operating conditions showed energy savings up to about 25% in comparison to a conventional drive relative to equal payloads.

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